Near Infrared Spectroscopy of G29.96−0.02:
The First Spectral Classification of the Ionizing Star
of an Ultracompact H II Region

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ABSTRACT

We have obtained the first classification spectrum and present the first direct spectral classification of the ionizing star of an ultracompact H II region. The ultracompact H II region is G29.96−0.02, a well-studied object with roughly twice solar metallicity. The near infrared K-band spectrum of the ionizing star exhibits C IV and N III emission and He II absorption, but lines of H I and He I are obliterated by nebular emission. We determine that the star has a spectral type of O5 to O7 or possibly O8. We critically evaluate limits on the properties of the star and find that it is compatible with zero-age main-sequence properties only if it is binary and if a significant fraction of the bolometric luminosity can escape from the region. G29.96−0.02 will now be an excellent test case for nebular models, as the properties of the ionizing star are independently constrained.

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1. Introduction

Ultracompact (UC) H II regions are formed by massive stars still embedded in their natal molecular clouds. They are luminous and relatively easy to detect throughout the galaxy at far infrared and centimeter wavelengths (Wood & Churchwell 1989). As such, they hold great potential for the study of the formation and properties of massive stars in different environments and at different metallicities. However, the many magnitudes of extinction to these objects has hindered their study; until recently the stars have had to be studied by their indirect and uncertain effects on the interstellar medium.

In this *Letter* we present the first near infrared classification spectrum of the ionizing star of an UC H II region and directly derive narrow limits on its effective temperature by comparison to the stellar atlas of Hanson, Conti, & Rieke (1996). The UC H II region is G29.96−0.02, a well-studied object with a metallicity of about twice solar (Simpson et al. 1995; Afflerbach, Churchwell, & Werner 1997). Our work is complementary to that of Watson et al. (1997), who directly measured the extinction and intrinsic magnitude of the star using imaging in the radio and near infrared and simple nebular physics. Combining these results, we are able to place the star on the H-R diagram with a high degree of reliability.

Our work motivates a critical re-evaluation of the conclusion of Watson et al. (1997), that the ionizing star of G29.96−0.02 shows evidence for the evolution predicted by Bernasconi & Maeder (1996), and our independent constraints on the properties of the ionizing star will provide an important test for nebular models. However, our main result is to demonstrate that the ionizing stars of at least some UC H II regions are now open for business in the near infrared.

2. Data

We obtained spectra of G29.96−0.02 on the night of 1997 June 18 UT with the FSPEC spectrograph (Williams et al. 1993) on the Multiple Mirror Telescope. The seeing was about 1 arcsec FWHM and the sky was clear. The spectrograph has a 1.2×32 arcsec slit and gave coverage from about 2.03μm to 2.21μm at a resolution of $\lambda/\Delta\lambda \approx 1000$.

We obtained twelve 4 minute spectra of the ionizing star of G29.96−0.02 to give a total 48 minutes of exposure. We interspersed observations of

G29.96−0.02 with observations of the nearby bright A1V star HR 7209.

Figure 1 shows near infrared Brγ and K-band images of G29.96−0.02 taken from Watson et al. (1997). The images show clearly the ionizing star at the center of a bright arc of nebular emission. A fainter fan of emission extends away from the arc to the north east. The spectrograph incorporates a slit viewing camera working in the H-band and so we were able to accurately position the slit and guide manually. We oriented the slit in elevation to simplify guiding and as a result the slit rotated on the sky between position angles of 6 deg and 40 deg. We nodded the ionizing star along the slit.

We extracted the stellar spectrum in a synthetic aperture of 1.2 arcsec width centered on the ionizing star. This aperture matches both the image quality and the slit width. We also extracted spectra of the bright arc of the nebula to the south and west and the fainter, extended fan of the nebula to the north and east using apertures from 1.2 to 3.6 arcsec either side of the ionizing star.

We corrected for atmospheric absorption using the spectra of HR 7209. We removed the Brγ absorption by fitting and adding a Gaussian. While this will leave systematic errors of as much as 10% in this region, the Brγ line is of limited use as it is heavily contaminated by nebular emission. We used a blackbody with a temperature of 9970 K (Code et al. 1976) for the intrinsic continuum of HR 7209.

Our twelve individual spectra of G29.96−0.02 exhibited subtle ripples over scales of tens of pixels, the result, we think, of our relatively narrow synthetic aperture. To counter these ripples, we divided each spectrum by a fit to the continuum, then averaged the ratios (with 2σ rejection) and the fits separately, and finally multiplied the average ratio by the average continuum fit to give an average spectrum. The distribution of the individual spectra about the average spectrum implies a S/N of about 300 and examination of regions of the spectrum away from nebular, photospheric, and teluric features suggests that this S/N is indeed being achieved, at least in some places.

Figure 2a shows the nebular arc spectrum. The fan spectrum is similar, except that it has a lower S/N and the He I 2.1120μm and 2.1132μm lines are relatively weaker by about 10%. Figure 2b shows spectra of the ionizing star. The spectrum marked 'A' is the total spectrum with no attempt to remove the neb-

ular contamination. To create the spectrum marked 'B', we scaled and subtracted the arc nebular spectrum so that the Brγ and He I 2.0581μm lines were neither in emission or absorption. To create the spectrum marked 'C', we scaled and subtracted the arc nebular spectrum so that the Brγ and He I 2.0581μm lines were unreasonably deep; the equivalent width of Brγ is about 33Å in spectrum C, but in OB stars it is never deeper than about 10Å (Hanson, Conti, & Rieke 1996). Thus, the real spectrum of the ionizing star lies between spectra A and C and is probably closely approximated by spectrum B, other than near the strongest nebular lines. (We used the arc spectrum to correct for nebular emission as it has a higher S/N than the fan spectrum. Thus, we will likely very slightly over subtract the He I 2.1120μm and 2.1132μm lines.) It can be seen from the difference in the continuum fluxes between spectra A and C in Figure 2b that the veiling contribution of the nebular continuum is only about 10–20%.

3. The Effective Temperature

The K-band spectral features of O stars are almost independent of luminosity class except for the Brγ and He I 2.0581μm lines, which are obliterated in our stellar spectrum by nebular emission. Thus, we can determine the effective temperature of the star from its spectrum but not its luminosity class.

Figure 3 shows our normalized spectra along with spectra from the spectral atlas of Hanson, Conti, & Rieke (1996) for O stars of type O3V to O9.5V (HD 93205, HD 168076, HD 93204, Cyg OB2 516, HD 168075, HD 467839, HD 101413, and HD 37468). The strong nebular contamination of the Brγ and He I lines means that we have no reliable information on these lines. Nevertheless, the characteristic spectral features of other ions are present in the spectrum of the ionizing star. First, the star clearly has strong C IV emission. Second, it has He II absorption. Third, recalling that spectrum C is oversubtracted and noting the asymmetry of the stellar 2.11–2.12μm feature compared to the nebular 2.11–2.12μm feature, the star has N III emission. The He II absorption and N III emission both imply that the star is kO8 or earlier and the strong C IV emission limits the star to kO5 to kO8 (cf. Table 6 of Hanson, Conti, & Rieke 1996). (The k in this notation is an indication that these are K-band spectral types not optical MK spectral types.) Normally, the strength of the N III and

C IV emission features would rule out spectral classes kO7 and kO8 because these features are weak in solar metallicy stars. However, the roughly twice solar metallicity of G29.96$-$0.02 may enhance the strength of these features.

Spectral classes of k05 to kO8 correspond closely to MK spectral classes of O5 to O8 (Hanson et al. 1996). This range corresponds to effective temperatures of about 46000 K to about 38500 K (Vacca, Garmany, & Shull 1996).

We also note that the C IV and He II lines seem broad with FWHM of about 500 km s^{-1}; we are planning to obtain spectra at higher resolution to investigate this further.

4. The Nature of the Star

One of the objectives of this study was to check the conclusions of Watson et al. (1997), who noted that the star had an evolutionary age in excess of about 10^6 yr in apparent contradiction to the estimated age of the UC H II region of only 10^5 yr. A zero-age main-sequence(ZAMS) binary could not satisfy their limits and they rejected the possibility of a close triple system as too unlikely. They suggested that the best explanation was the idea of Bernasconi & Maeder (1996), that a massive star evolves as it accretes.

Figure 4 shows our limits on the effective temperature and the limits from Watson et al. (1997) on the effective temperature, luminosity, and distance. Also shown are evolutionary tracks and isochrones for the $Z = 2Z_\odot$ models of Meynet et al. (1994). Our new limits are consistent with those of Watson et al. (1997). Taken together, the limits are consistent with a single or binary star with an apparent age of between about 1 and 2×10^6 yr.

Might the apparent age of the UC H II region be wrong? Long lived UC H II regions have recently been proposed by De Pree, Rodríguez, & Goss (1995) and García-Segura & Franco (1996). The basic idea is that the densities in molecular cores can be large enough to stall the expansion of the UC H II region. We note, however, that G29.96$-$0.02 is not centered on the cloud core (see Figure 6 of Watson et al. 1997) and appears to have entered a champagne flow phase (Lumsden & Hoare 1996). For the UC H II to be of order 10^6 yr old would require that its H II region had been confined for most of this time but recently released. Both the confinement, given the location

3

of the core, and the fine tuning of the release seem unlikely to us. We conclude that an age of order 10^5 yr is likely to be correct.

Might the limits on the properties of the ionizing star be wrong? The limits of Watson et al. (1997) on the m_K and distance and our limits on the effective temperature seem to be very robust. The m_K depends only on directly observed quantities and the simple nebular physics of ionized hydrogen to determine A_K. Widening the distance limit of 5 kpc $\leq d \leq$ 10 kpc to 4 or 11 kpc would imply unacceptably large random velocities of 30 km s^{-1}. Our effective temperature limit is derived by comparison of the observed spectrum of the ionizing star to well-calibrated spectral standards.

What about the limit on the effective temperature derived by Watson et al. (1997) from a consideration of the observed $m_{\rm bol}$ and m_K? If, for the moment, we ignore this limit, we can satisfy the other limits in the small corner of the available parameter space occupied by binaries of O5 or O5.5 ZAMS stars at 5 kpc. (Earlier or later single stars or binaries are still forbidden by the robust limits on the effective temperature, m_K, and distance.) Such a binary would produce 20–50% more than the 3σ upper limit or 50–100% more than the measured bolometric luminosity for the region; thus, a correspondingly large fraction must escape the UC H II region. A close binary might also explain the broad photospheric lines seen in the spectrum. Whether this explanation is more acceptable than the one offered by Watson et al. (1997) is left to the judgement of the reader.

If we are to accept the idea that the ionizing star in G29.96−0.02 evolved significantly as it accreted, we must provide an explanation for why HD 93250 and O stars in M17 apparently have not (Hanson, Howarth, & Conti 1997). The time allowed for evolution to proceed during the accretion phase is inversely proportional to the mean accretion rate. It is possible, then, that accretion proceeded sufficiently quickly in M17 and HD 93205 that evolutionary effects are not noticeable, but slowly enough in G29.96−0.02 that they are. Models run at a number of accretion rates at both solar and twice solar metallicity are needed to investigate this.

If the broad photospheric lines seen in our spectrum are the result of very rapid rotation, the von Zeipel effect will act to reduce the effective temperature of the equatorial regions. This could reconcile our luminosity and effective temperature with those of a single main-sequence star. However, we are doubtful that the effect can lower the temperature by the several thousand degrees required.

5. Nebular Models

Simpson et al. (1995) and Afflerbach, Churchwell, & Werner (1997) have modeled the far infrared emission lines of G29.96−0.02 and found best fits with ionizing stars that have effective temperatures that are cooler than our lower limit of 38500 K. Similarly, Faison et al. (1997) have recently modeled the dust re-emission of G29.96−0.02 and find a best fit with ionizing stars that have luminosities that are below our lower limit on the luminosity of the region. Clearly, satisfying our constraints on the stellar properties while correctly predicting the mid and far infrared emission will be an excellent test of models of the nebular emission. Success may require more complex models that pay attention to the geometry of G29.96−0.02, in particular its lack of spherical symmetry and wide range of ionization parameters.

In the meantime, we can use our limits to investigate the ionization in the nebula. The recombination rate of 1.35×10^{49} s^{-1} at 5 kpc is a lower limit to the Lyman continuum photon flux of the ionizing star, as dust can absorb ionizing photons and, possibly, ionizing photons can escape from the nebula. We calculated this recombination rate from the intrinsic Brγ flux given by Watson et al. (1997) and the Case B nebular models of Hummer & Storey (1987). If we use a fit to Figure 13 of Schaerer & de Koter (1997) to give $q_0(T)$ and $L = 4\pi R^2 \sigma T^4$ to give the Lyman continuum photon flux $Q_0(L, T) = 4\pi R^2 q_0$, then we find that the Lyman continuum flux exceeds the effective recombination rate by factors of about 1.5 (at O8) to about 4 (at O5). This suggests that either dust is a significant competitor for ionizing photons or that a significant fraction of the ionizing photons are escaping.

6. Summary

We have successfully obtained a K-band classification spectrum of the ionizing star of the UC H II region G29.96−0.02. The lines of H I and He I are obliterated by nebular emission, but the spectrum shows C IV and N III emission and He II absorption. Using the classification scheme of Hanson, Conti, & Rieke (1996), we are able to restrict the star to spectral classes of O5 to O8 which correspond to effective

temperatures of 46000 K to 38500 K.

When we combine our effective temperature limits with the absolute magnitude determined by Watson et al. (1997), we can place the star on the H-R diagram using only the relatively well-understood properties of the stellar photosphere and the ionized gas. Our limits are more robust than previous ones, which relied on a mixture of assumptions and models for the influence of the star on the surrounding ISM.

One direct result of this work is to provide a test case for models of the nebular line and dust emission; these must now satisfy the independent constraints on the effective temperature and luminosity of the ionizing star. In this context, the recently obtained ISO SWS and LWS spectra of G29.96−0.02 will be a valuable resource.

At moderate resolution ($\lambda/\Delta\lambda \sim 1000$), the strong nebular emission in UC H II regions obliterates the stellar H I and He I features leaving us with just the C IV, N III, and He II features in the K-band. The spectral types that can be determined from these features are quite rough: O3 to O4 (N III emission and He II absorption but no C IV emission), O5 to O8 (both N III and C IV emission and He II absorption), and O9 or later (none of these). Observations at high resolution ($\lambda/\Delta\lambda \sim 10000$) may be able to resolve the broad stellar lines from the narrow nebular lines, but will be challenging.

This is the first time that the effective temperature of the ionizing star of a UC H II region has been determined directly. This technique may be feasible in other UC H II regions, although nebular veiling and higher extinction may be serious problems. This work is a further demonstration that K-band spectral classification, when combined with near infrared imaging, is a uniquely powerful tool for the study of very young massive stars.

REFERENCES

Afflerbach, A., Churchwell, E., & Werner, M. 1997, ApJ, 478, 190

Bernasconi, P. A., & Maeder, A. 1996, A&A, 307, 829

Code, A. D., Davis, J., Bless, R. C., & Hanbury Brown, R. 1976, ApJ, 203, 417

De Pree, C. G., Rodríguez, L. F., & Goss, W. M. 1995, Rev. Mexicana Astron. Astrofis., 31, 39

Faison, M., Churchwell, E., Hofner, P., Hackwell, J. A., Lynch, D. K., & Russell, R. W. 1997, in preparation

García-Segura, G., & Franco, J. 1996, ApJ, 469, 171

Hanson, M. M., Conti, P. S., & Rieke, M. J. 1996, ApJS, 107, 281

Hanson, M. M., Howarth, I. D., & Conti, P. S. 1997, ApJ, Nov 10 (in press)

Hummer, D. G., & Storey, P. J. 1984, MNRAS, 224, 801

Lumsden, S. L., & Hoare, M. G. 1996, ApJ, 464, 272

Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97

Schaerer, D., & de Koter, A. 1997, A&A, 332, 598

Simpson, J. P., Colgan, S. W. J., Rubin, R. H., Erickson, E. F., & Haas, M. R. 1995, ApJ, 444, 721

Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914

Watson, A. M., Coil, A. L., Shepherd, D. S., Hofner, P., & Churchwell, E. 1997, ApJ, Oct 1 (in press)

Williams, D., Thompson, C. L., Rieke, G. H., & Montgomery, E. F. 1993, Proc. SPIE, 1308, 482
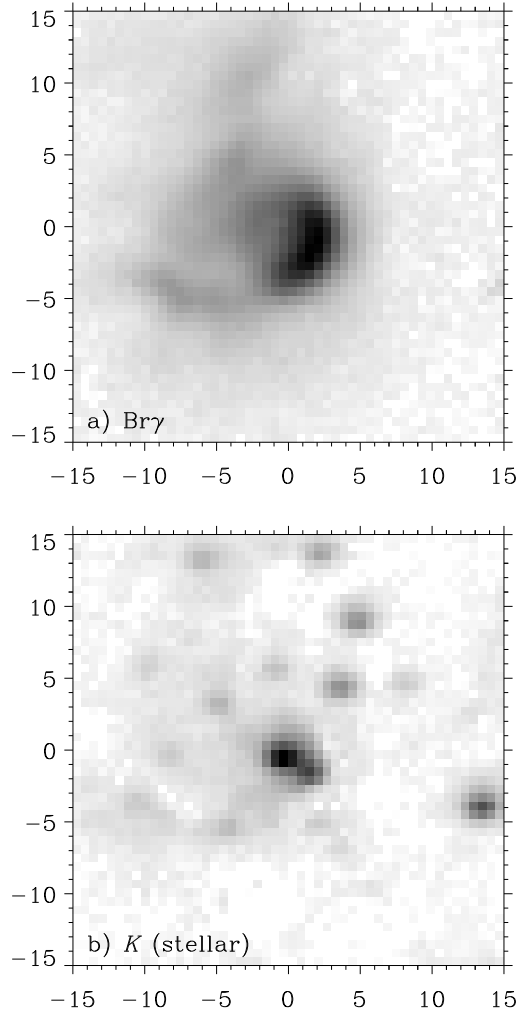
Wood, D. O. S., & Churchwell, E. 1989, ApJ, 340, 265

Fig. 1.— (a) Brγ and (b) *K*-band images of the region around G29.96−0.02 from Watson et al. (1997). The axes are marking arcsec. The Brγ image has been scaled and subtracted from the *K* image to suppress nebular emission. Note the arc of bright nebular emission, the fan of fainter nebular emission extending to the north-west, and the ionizing star at the center of the arc.
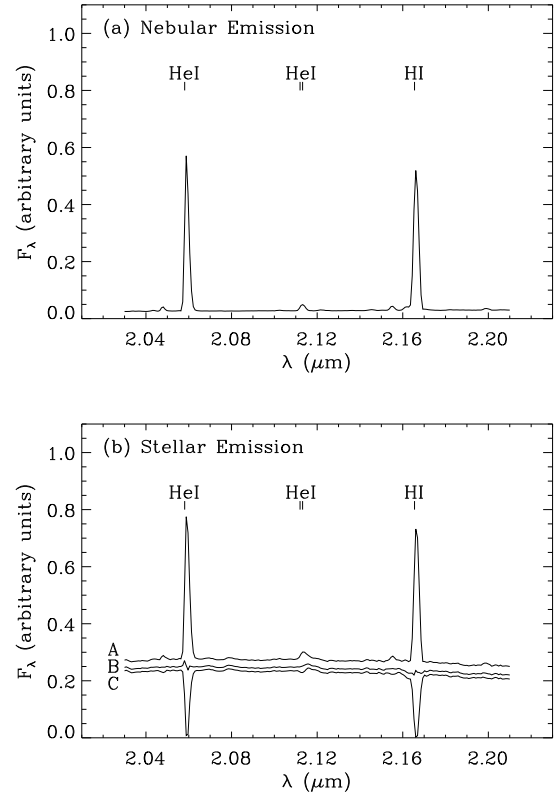

Fig. 2.— (a) The nebular arc spectrum. (b) The ionizing star spectra. As described in Section 2, spectrum A is not corrected for nebular emission, spectrum B is corrected to leave the Brγ and He I 2.0581μm lines neither in emission or absorption, and spectrum C is overcorrected.
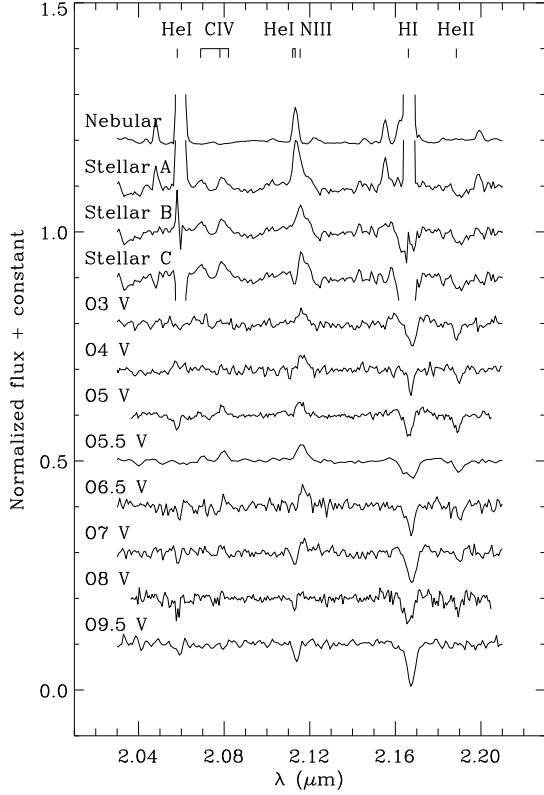
Fig. 3.— Normalized spectra of the nebula and ionizing star from this work and of comparison stars from Hanson, Conti, & Rieke (1996).
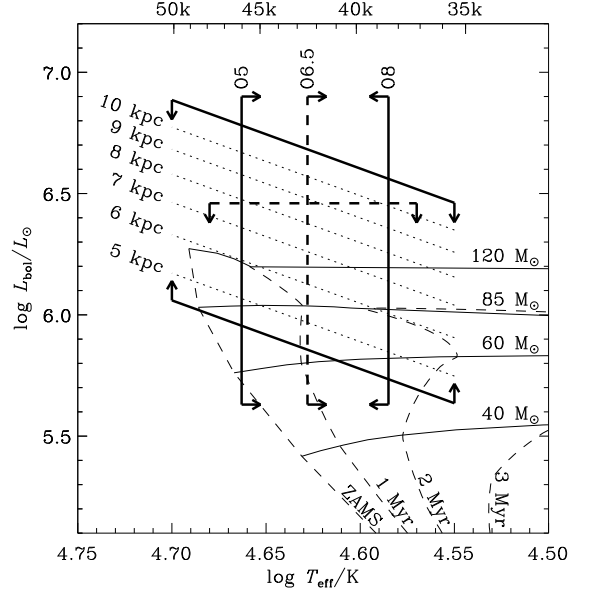

Fig. 4.— A theoretical H-R diagram for the ionizing star. The temperature limits derived from our spectral classification are shown by thick solid vertical lines. The luminosity limits determined by Watson et al. (1997) from limits on the distance and m_K are shown by sloping thick solid lines. The limits on the effective temperature and luminosity derived by Watson et al. (1997) from limits on the distance, m_K, and m_{bol} are shown as thick dashed lines. The thin dotted lines show the loci where the m_K is exactly that measured at different distances. Also shown are tracks and isochrones of the $Z = 2Z_{\odot}$ models of Meynet et al. (1994). The thin solid lines are tracks for 120, 85, 60, and $40 M_{\odot}$ models and the thin dashed lines are the ZAMS, 1, 2, and 3×10^6 yr isochrones.